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Application of an advanced real options approach for renewable energy generation projects planning

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ABSTRACT

Nowadays, there is growing interest in renewable energy (RE) generation projects due to environmental and sustainability concerns. However, initial costs and uncertainties caused by RE source variability, changes in support schemes, and other factors can render RE projects unattractive when subject to conventional financial assessment. Initial research suggests that the value of RE projects can be enhanced by the application of real options (RO) theory in the planning and evaluation of such projects. Literature on application of RO planning in RE generation projects is limited, and typically focuses solely on flexible investment decisions and neglects flexible designs. A more comprehensive approach should address flexibility in designs.

This paper proposes an advanced RO methodology for RE generation projects planning, and illustrates the methodology using variations of a hydropower case study. The fundamental differences between advanced RO approaches and other techniques are illustrated on a simple case study. The complete version of the proposed advanced methodology is then compared against other available tools. The results show higher expected profits for projects planned with the advanced RO methodology.

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1. Introduction

The world's ever growing dependence on electrical energy is reflected in significant investments in electricity generation projects [1]. An increasing percentage of such investments are targeted at RE generation projects due to: environmental concerns

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Nomenclature

a	head (m)
b	scenario probability
B	benefits function
c	costs factor
C	costs function
Ct	costs (10^9 $)
d	discount rate (%)
EC, ec	economic constraints
f	power plant efficiency
fc	fixed costs (10^9 $)
$\underline{h}$	hours in a year (h)
H	generation capacity (MW)
K	amount of scenarios used for the simulations
O	opportunity loss
p	price of electricity ($/kWh)
P	power generated (MWh)
pf	power factor
pwc	present worth factor for costs
pwr	present worth factor for revenue
R	investment timing decisions matrix $\in [0\ 1]$
Rv	revenue (10^3 $)
TC, tc	technical constraints
To	total opportunity loss
U	value according to an evaluation criterion
V	storage capacity (10^6 m^3)
vcv	reservoir's variable cost (10^3 $/$m^3$)
vch	power plant's variable cost (10^9 $/MWh)
w	additional water inflow (m^3/s)
W	evaluation criterion weight value
X	water outflow (m^3/s)
y	seconds in a year (10^6 s)
Y	design parameter

Subscripts

i	index of time
j	index of site
k	index of scenario
l	index of time (Auxiliary)
m	index of evaluation criteria
n	index of investment scheme
r	index of real option

Superscripts

Max	maximum possible value
Best	best value (higher or lower) according to an evaluation criterion

[2], emission targets under the Kyoto protocol [3], renewable support schemes such as feed-in tariffs and investment grants [4], as well as upgrades in RE technologies achieved through research and development [5,6]. However, REs tend to be less competitive than other generation technologies, especially in the absence of adequate support policies [2,7]. This suggests that additional economic drivers might be necessary to promote investment in RE generation projects.

A potential and unexploited economic driver for RE generation projects is the value of flexibility. In this paper, flexibility refers to the capability of managers to modify projects according to the evolution of uncertainty. This flexibility to adjust projects can enhance the projects worth [8], yet it is typically disregarded in the planning process of RE generation projects.

Generation projects, including RE projects, are typically assessed with Discounted Cash Flows (DCF) methods [9]. DCF methods neglect flexibility, which can lead to project undervaluation. On the other hand, RO methods take account of flexibility, and literature suggests that RO methods are more suitable for RE project assessment [10,11]. Flexibility value captured by RO methods can enhance the value of RE generation projects. However, RO literature regarding RE generation projects is limited and the theory requires further development to take advantage of more flexibility value within RE generation projects.

Flexibility exists whenever projects are influenced by uncertainty, and means to adjust them (flexibility sources) are available. Typical uncertainty sources in RE generation projects are the price of electricity, RE source, and technology [12]; whereas flexibility sources addressed by RO methods are (i) flexible investment timing and (ii) flexible design [13]. Based on these flexibility sources, the following classification is proposed for RO planning methodologies:

- Typical RO: RO methodologies addressing flexibility sources independently.
- Advanced RO: RO methodologies addressing both flexibility sources simultaneously or alternately.

In other words, typical RO methodologies identify and assess flexible investment timing regardless of the projects' characteristics (treating projects as black boxes), or flexible projects' designs regardless of possible investment timing. On the other hand, advanced RO methodologies identify flexible projects' designs based on possible investment timings and vice versa.

In this paper, an advanced RO methodology for RE generation planning is proposed. The methodology is illustrated and compared with other available planning tools using variations of a hypothetical hydropower case study.

2. RO theory

RO theory is the extension of financial options theory for real asset assessment. A real option can be defined as the right, without obligations, to make an investment decision concerning real assets (i.e. defer, build, abandon, alter, switch, etc.). This flexibility can enhance the value of projects [14].

The evolution of financial options theory, and thus creation of RO theory, began in the early 70s due to growing dissatisfaction with DCF methods [15], and significant breakthroughs in options pricing brought about by the development of the Black–Scholes equation [16]. In the late 70s, the term "real option" was introduced, and the RO theory was recognized as a new research area [17]. Introduction of RO theory triggered research addressing assessment of projects in different areas, including RE generation projects.

Nowadays, relevant RO literature regarding RE and other generation technologies is still scarce, and mainly consists of studies focused on flexible investment timing that neglect projects' designs. Correia et al. [18] analyze flexible investment timing for generation projects. The characteristics of the project are only reflected in costs. Chung-Hsiao and Min [19] study the effect of market interdependency on the flexible investment timing of generic generation projects. Botterud et al. [20] present a study involving different generation technologies. However, the technologies are never specified.

The same trend can be observed in RO literature regarding other types of projects, as can be seen in [21–23]. This shows that, current RO literature commonly disregards flexible designs. A reason for this tendency can be the underlying difficulties associated with assessment of flexible designs. Such assessments require understanding of projects' technologies, and resulting RO tend to be

path-dependent and highly interdependent [24]. Regardless, a few examples of literature addressing flexible designs can be found. Examples of such literature include [25,26]; where the RO analyses are greatly simplified by defining flexible designs empirically.

The next step in RO theory evolution would involve methods for flexible design formulation, and the combination of flexible designs and investment timing. A first attempt to take such a step was the introduction of a RO approach that, for simplification, will be referred to as Tao Wang's Methodology (TWM) [27]. TWM can formulate flexible designs, but only addresses flexible investment timings and designs independently. A more advanced approach would need to assess both flexibility sources simultaneously or iteratively.

Advanced RO approaches have potential to explore flexibility value more than current RO methodologies. Accordingly, they could enhance significantly the value of RE generation projects. An advanced RO planning methodology is presented in the following section.

3. Methodology

The proposed RO planning methodology is divided into two stages. First, a mathematical programming model, based on a path-dependant scenario tree, is used to identify optimal investment timings and designs. The model's output is an investment scheme based on the decision nodes considered for the scenario tree. Later, Monte Carlo simulation [28] is used to compute the expected value of the project when implementing the investment scheme. If several investment schemes are proposed, minimax regret (opportunity loss) [29] is used to differentiate them.

The optimization model's objective function involves profits maximization throughout the path-dependant scenario tree. The model's variables are investment timing, and design parameters, as can be seen in (1):

$$\text{Maximize}: \quad \sum_k b_k \sum_i \sum_r [B_{i,r}(Y_{k,r}, R_{k,i,r}) - C_{i,r}(Y_{k,r}, R_{k,i,r})] \quad (1)$$

The model's constraints are based on economic and technical limitations of the project, as shown in (2) and (3):

$$TC(Y_k, R_k) \geq tc \quad (2)$$

$$EC(Y_k, R_k) \geq ec \quad (3)$$

Simulation requires investment schemes and stochastic models of relevant uncertainty sources such as, for example, electricity prices and environmental policies. The outputs are expected implementation values, and a comparative study (based on opportunity loss) of the different investment schemes analyzed. Opportunity loss calculation is based on selected decision criteria, for example net present value and internal rate of return, and a weighted sum of objective functions method [30]. Investment scheme selection is based on minimum opportunity loss. These computations are shown in (4) and (5):

$$O_{m,n} = \frac{1}{K} \sum_k \left| U_{k,m}^{Best} - U_{k,m,n} \right| \quad (4)$$

$$To_n = \sum_m W_m O_{m,n} \quad (5)$$

As can be seen, the models require specific economic and technical constraints related to the projects. The formulation of such constraints will be illustrated in the case study presented in the next section.

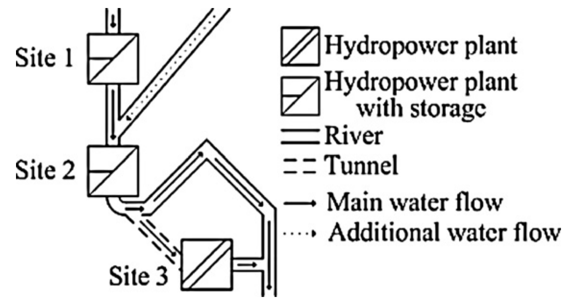

Fig. 1. River basin.

4. Case study

4.1. Description of the case study

A Generation company can build hydropower plants, and its corresponding dams or tunnels, in three locations along a river basin as shown in Fig. 1. Each location has different characteristics which affect the design limits and costs of possible hydro power plants. The company will assess investments based on expected profits.

The project's budget allows construction of at most one power plant every 10 years. Construction cannot be delayed more than 20 years. Operation lifetime is assumed to be 60 years. Relevant sources of uncertainty are the price of electricity (modelled with Geometric Brownian Motion), and water flows (modelled with log-normal distributions). For further details on the models refer to [27].

4.2. Simplification of the case study

A simplification of the case study is used to illustrate the main differences between traditional DCF, typical and advanced RO methodologies. The simplifications are the following:

- The river basin is simplified as is shown in Fig. 2.
- All sites' design limits and storage capacity are assumed to be the same.
- Water flow stochasticity is neglected.
- An operation lifetime of 30 years is assumed.
- Operation begins at full capacity five years after construction.
- Costs for site two and three are assumed 0.5 and 1.0% more expensive than costs for site one.
- All parameters used for this case study are given in Table 1.

The optimization model adjusts the design variable (H) and investment timings (R) to maximize profits. This is shown in (6)–(8):

$$\text{Maximize}: \quad \sum_k b_k (0.001 R v_k - 1000 C t_k) \quad (6)$$

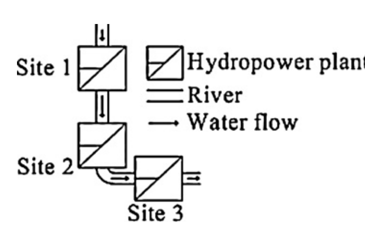

Fig. 2. Simplified river basin.

Table 1
Parameters for the simplified case study.

Parameter	Value	Units
a	200	m
b	[0.139 0.233 0.233 0.395]	
d	8.6	%
p	[36.24 36.24 36.24 36.24 45.18 45.18 29.11 29.11 56.29 36.24 36.24 23.31]	$/kWh $\times 10^{-3}$
f	0.7	
fc	1.0161	$ $\times 10^9$
h	8760	h
H^{Max}	3200	MW
pf	0.35	
pwc	[1 0.438 0.192]	
pwr	[2.8256 0.00 0.00 3.1088 1.2383 0.00 1.4465 1.9963 1.4175]	
y	31.536	s $\times 10^6$
vcv	0.00008070	$/m^3 $\times 10^3$
vch	0.00010632	$/MWh $\times 10^9$
V^{Max}	12,500	m^3 $\times 10^6$
w	[590 0 0]	m^3/s

$$Rv_k = \sum_i \sum_j P_{i,j,k} p_{i,k} \sum_{l=1}^{i} pwr_{i,l} R_{j,l,k} \quad (7)$$

$$Ct_k = \sum_i pwc_i \sum_j R_{i,j,k} c_j (fc + vcvV + vchH_{k,j}) \quad (8)$$

At most, one hydropower plant can be built every time period (10 years), as shown in (9):

$$\sum_i R_{i,j,k} \le 1 \quad \forall_{j,k} \quad (9)$$

Generation (H) and storage (V) capacities have maximum limits as shown in (10) and (11):

$$V \le V^{Max} \quad (10)$$

$$H_{j,k} \le H^{Max} \quad \forall_{j,k} \quad (11)$$

Power generation is a function of generation capacity, water flows, dam shape, and storage as shown in (12)–(14):

$$P_{i,j,k} \le 2.73 fy X_{i,j,k} a^2 \quad \forall_{i,j,k} \quad (12)$$

$$P_{i,j,k} \le pfhH_{j,k} \quad \forall_{i,j,k} \quad (13)$$

$$V \ge 0.14a^2 \quad (14)$$

Construction and operation of hydropower plants affect water flow as shown in (15) and (16):

$$X_{i,0,k} = 0 \quad \forall_{i,k} \quad (15)$$

$$0.25V \sum_{l=1}^{i} R_{l,j,k} \le (w_j + X_{i,j-1,k} - X_{i,j,k}) \cdot y \quad \forall_{i,j,k} \quad (16)$$

Timing and design options are formulated based on a binomial path-dependent scenario tree addressing three time periods, as shown in (17)–(19):

$$R_{1,j,1} H_{j,1} = R_{1,j,2} H_{j,2} = R_{1,j,3} H_{j,3} = R_{1,j,4} H_{j,4} \quad \forall_j \quad (17)$$

$$R_{2,j,1} H_{j,1} = R_{2,j,2} H_{j,2} \quad \forall_j \quad (18)$$

$$R_{2,j,3} H_{j,3} = R_{2,j,4} H_{j,4} \quad \forall_j \quad (19)$$

The model is a mixed integer non linear programming model. Such models can be solved with non linear optimization software, such as GAMS®, or a combination of linear optimization software and linearisation tools, such as Xpress-IVE® and separable programming techniques [31]. Additionally, due to the size of the case study, the model can be treated as a linear optimization problem. This can be achieved by conducting an exhaustive search [32] for all possible investment decisions (R) (2715 combinations), and solving them individually with linear optimization software. The exhaustive search can be conducted using MATLAB®, whereas the optimization can be performed with Xpress-IVE®.

5. Evaluation of the simplified case study

5.1. Traditional DCF analysis simulation

DCF analyses assume irreversible investments without delay possibilities (now or never decisions) [14]. To simulate a DCF approach, a greedy optimization [32] based on the net present value (NPV) calculation is used. First, optimal design parameters for all hydropower plants are determined for the first time period using the optimization model. Designs are shown in Table 2. Afterwards, investment timing is determined with the greedy optimization. The resulting investment scheme can be seen in Fig. 3.

Based on this methodology, the simplified hydropower project expected NPV is 70$ $\times 10^6$.

Table 2
Fixed design parameters for the simplified case study.

Site	H (MW)
1	2200
2	2200
3	2200

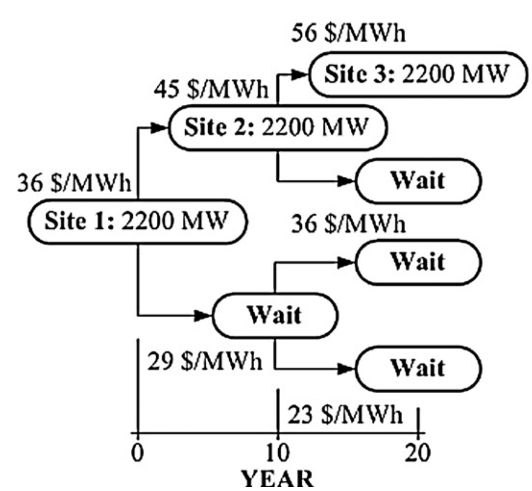

Fig. 3. DCF method's investment scheme for the simple case study.

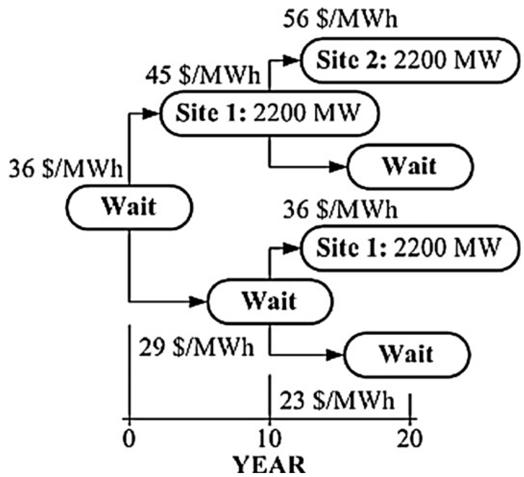

Fig. 4. Typical RO method's investment scheme for the simple case study.

5.2. *Typical RO simulation*

To simulate a typical RO analysis, design flexibility is neglected. A typical RO analysis considers flexible investment decisions by assessing the option to delay investments and gain information about the evolution of uncertainty. To simulate this approach, design parameters are fixed to those given earlier in Table 2, and optimal investment timing is determined with the optimization model. The resulting investment scheme is shown in Fig. 4.

The results show that it is convenient to delay investment for at least one time period. This flexible investment decision enhances expected NPV from 70 to 97$ $\times$ 10^6.

5.3. *Advanced RO simulation*

Advanced RO analyses exploit the value of flexible investment timing and designs. This considers the value of delaying investment and adjusting design parameters based on selected investment timing. This approach is simulated using the optimization model presented in the previous section. The resulting investment scheme is shown in Fig. 5.

The advanced RO methodology also proposed delaying investment until the second period. In addition, it suggested a lower generation capacity for the possible hydropower plant located on site two (from 2200 MW to 2000 MW). This flexibility, in the project's design and timing, increases the expected NPV from 97 to 98$ $\times$ 10^6.

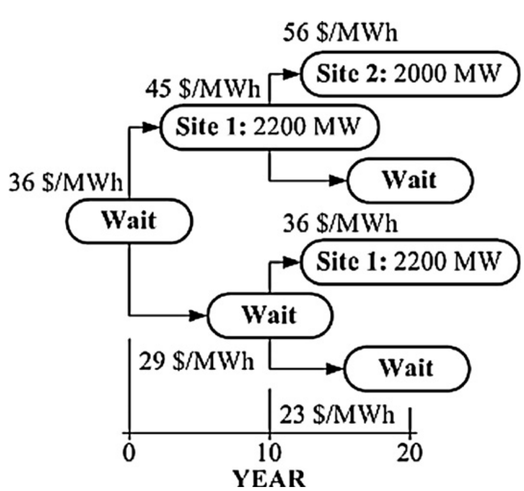

Fig. 5. Advanced RO method's investment scheme for the simple case study.

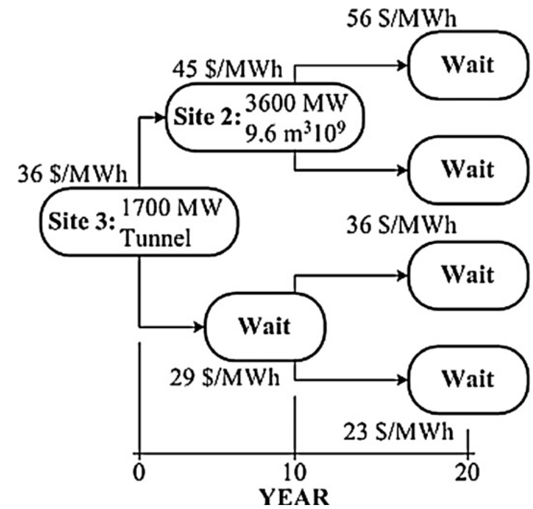

Fig. 6. DCF method's investment scheme for the case study.

It can be argued that this study does not show significant economic advantages of advanced RO methodologies over typical RO approaches. Nevertheless, it is a simple and replicable study that illustrates the fundamental differences between the three approaches. The economic advantages of advanced RO methodologies will be addressed in the following section.

To summarize this section, traditional DCF methodologies focus on selecting the best investments for the time being; typical RO approaches enhance the value of projects by either addressing flexible investment timing, as shown in the case study, or flexible designs; and advanced RO methodologies further enhance the value of projects by considering flexible designs and timing simultaneously, as shown in the case study, or alternately.

6. Evaluation of the complete case study

6.1. *Investment scheme formulation*

In this section, the complete case study is assessed with available approaches representing DCF, typical and advanced RO planning methodologies. DCF methodologies are represented by a greedy optimization based on the calculation of NPV. Typical RO methodologies are represented Tao Wang's Methodology (TWM) [27], which is the most comprehensive typical RO planning methodology found in the literature survey. Advanced RO approaches are represented by the methodology proposed in this paper.

In order to define project designs for the DCF analysis, part of TWM is used. The investment scheme formulated with the DCF methodology is shown in Fig. 6; whereas the designs used for the analysis are presented in Table 3.

First, TWM formulates several design alternatives using an optimization model based on possible values of underlying sources of uncertainty. The designs are given in Table 4. A second optimiza-

Table 3
Fixed design parameters for the case study.

Site	Generation (MW)	Storage ($m^3 \times 10^6$)
1	3200	12,500
2	3600	9600
3	1700	0

Table 4
Design parameters formulated with TWM.

Design parameter	Site	First alternative	Second alternative	Third alternative
Generation (MW)	1	1723	1946	1966
	2	3600	3600	3600
	3	1700	1700	1700
Storage ($m^3 \times 10^6$)	1	9593	12,242	12,500
	2	9600	9600	9600
	3	0 (tunnel)	0 (tunnel)	0 (tunnel)

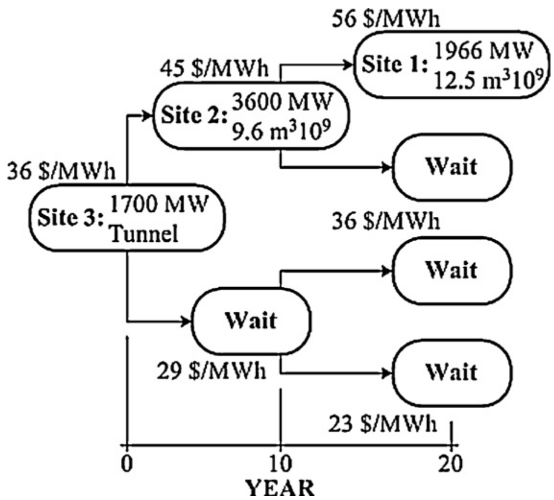

Fig. 7. TWM's investment scheme for the case study.

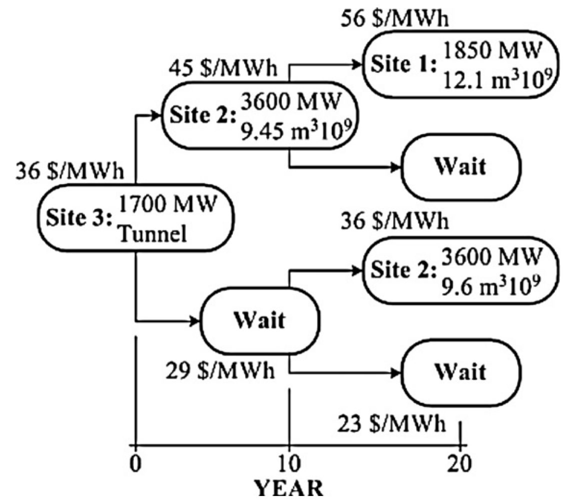

Fig. 8. Advanced RO' investment scheme for the case study.

tion model is then used to select a design alternative and calculate its optimal investment timing. The resulting investment scheme is shown in Fig. 7.

Table 5 shows different design alternatives for site one; whereas the design alternative remains unchanged for other sites. This indicates that flexible designs were only identified for site one.

The proposed advanced RO methodology adjusts design parameters and searches for optimal investment timing in a single process. The investment scheme formulated with this methodology is shown in Fig. 8.

6.2. Investment scheme evaluation

Investment schemes are evaluated using Monte Carlo simulation (5000 scenarios) and opportunity loss criteria. The simulation requires investment schemes (formulated in the previous subsection), and stochastic models for relevant sources of uncertainty namely electricity price and water flows.

The electricity price is modelled annually using Geometric Brownian Motion and considering an initial value of 36.24 $/MWh, a drift rate of 0.33% and a volatility of 6.96%. The water flows are modelled seasonally (every six months) with lognormal distributions. The main river's mean water flow is 374 and 283 m^3/s, with a standard deviation of 87.7 and 45.4% respectively. The mean water flow of the additional river is 389 and 154 m^3/s, with a standard deviation of 89.8 and 9.7% respectively.

Opportunity loss is based on NPV. However, for illustrative purposes, the net value (NV) will also be employed. The simulation results are shown in Tables 5 and 6.

As can be seen in Table 5, the advanced RO investment scheme offers the highest expected value, followed by investments determined using typical RO and DCF methodologies.

It can be seen, in Table 6, that the opportunity loss of the advanced RO investment scheme is greater than zero, but significantly the lowest. This suggests that although the investment scheme is not the optimal in all possible scenarios, it is the optimal or close to the optimal investment scheme in most scenarios. It can also be seen that NV rather than NPV loss of opportunity is more favourable for RO investment schemes. To explore this fact, the NV and NPV probability distribution functions are shown in Figs. 9 and 10.

The curves behaviour is more similar for NPV than for NV, this is caused by the time value of money. In this case study, RO for flexible investment timing balance timing benefits (additional profits) against timing costs (time value of money).

Therefore, presented results, besides being dependent on the stochastic models selected, can be significantly dependent on the discount rate.

6.3. Sensitivity analysis

To address the robustness of the presented results, a sensitivity analysis is conducted for the Monte Carlo simulation. The analysis

Table 5
Mean expected NPV and NV for all investment schemes.

Investment scheme	NPV ($\$ \times 10^6$)	NV ($\$ \times 10^6$)
DCF	1159	19,595
Typical RO	1160	22,556
Advanced RO	1180	28,252

Table 6
Mean expected opportunity loss for all investment schemes.

Investment scheme ($\$ \times 10^6$)	NPV regret ($\$ \times 10^6$)	NV regret
DCF	34	8805
Typical RO	32.5	5844
Advanced RO	13.3	148

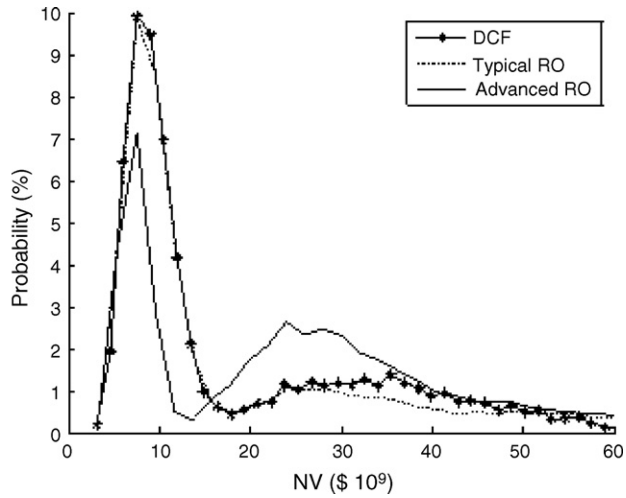

Fig. 9. Net value probability distribution function.

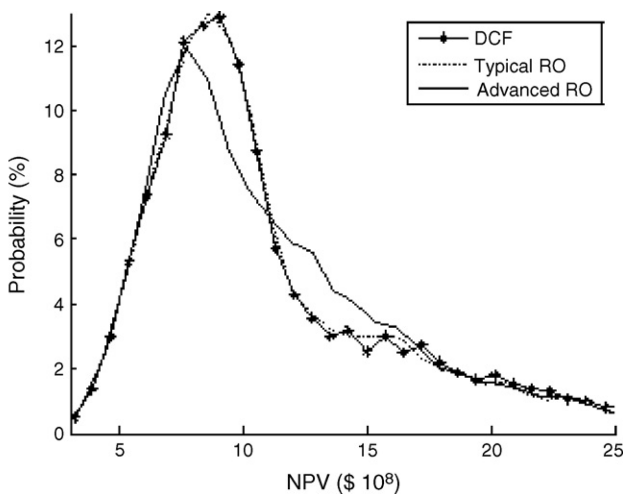

Fig. 10. Net present value probability distribution function.

Table 7
Probability of being the best or worst investment scheme.

Investment scheme	NPV best (%)	NV best (%)	NPV worst (%)	NV worst (%)
DCF	0.0	0.0	59.2	100
Typical RO	0.0	0.0	40.7	0.0
Advanced RO	100	100	0.0	0.0

considers 10% variations in discount rate, electricity price model's drift and volatility, and average water flows. The results are shown in Table 7.

It can be seen that, within the scope of the sensitivity analysis, the advanced RO investment scheme is the best alternative.

7. Conclusion

This paper has discussed the importance of RE generation projects, as well as the necessity for additional economic drivers for investments in RE. RO theory is explored as a possible economic driver for RE projects. It is concluded that RO theory requires further development to significantly enhance RE projects. Consequently, advanced RO methodologies are suggested to provide this improvement.

An advanced RO methodology is introduced and illustrated with variations of a hydropower case study.

A simplification of the case study is used to illustrate the theoretical difference between DCF, typical and advanced RO methodologies. In the absence of either flexible designs or flexible investment timing, an advanced RO methodology behaves as a typical RO approach. Moreover, in the absence of all flexibility, a typical RO approach behaves as a DCF technique. This suggests that the lowest value an advanced RO methodology would provide would be the optimal value according to a traditional DCF methodology.

The complete case study allowed a comparison of the proposed advanced RO methodology against other planning methodologies. Results showed higher expected profits for projects planed with the advanced RO methodology.

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